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Optimization of natural resource management: Application to French copper cycle

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ABSTRACT

An innovative resource flow optimization model is proposed that aims at helping decision makers to choose the best resource management policies at national and international scales. This model has been developed and validated on French copper cycle, but can easily be extended to any country or metal. A mathematical formulation of all the in- and outflows of the resource, as well as stocks in the technosphere and waste management, including recycling, has been developed. The complexity of resource cycle led to the introduction of 47 decision variables and resulted in a Mixed-Integer Non-Linear Programming formulation. The resource cycle efficiency has been assessed through four indicators regarding costs, greenhouse gas emissions, energy consumption and resource losses. The NSGA II genetic algorithm methodology has been selected as an optimization strategy. Monobjective optimizations have firstly been conducted for each of the four criteria: the results showed that very different management strategies are needed depending on the targeted criteria. Multiobjective optimizations have thus been conducted coupled with the decision support tool TOPSIS to find an optimal compromise solution. As expected, the selected solution highlights the importance of developing a recycling channel for Waste from Electrical and Electronic Equipment in France.

1. Introduction

Economic development is strongly dependent on the use of natural resource and the growing demand creates a permanent pressure on the resource base, so that natural resource management is an important issue that has to be treated carefully. Indeed, many materials, including metals, are essential to our lifestyle, while their availability is limited and their exploitation is both capital and energy intensive. The growing metal stocks in our society can thus be seen as huge mines, which has been democratized with the "urban mining concept", defined as the "process of reclaiming compounds and elements from any kind of anthropogenic stocks, including buildings, infrastructure, industries, products (in and out of use), environmental media receiving anthropogenic emissions, etc." (Cossu and Williams, 2015). Metals possess the advantage that they are infinitely recyclable with no loss of quality. In that context, scrap-metal-recycling, that provides resources to the basic manufacturing sector, plays a pivotal role while conserving natural resources and protecting the environment. Actually, recycling can be viewed as a way to mitigate negative impacts on increasing metal demand and to assure the potentials of economic growth. Scrap-recycling facilities are rich with resources that can be reused, at a fraction of the cost to mine and refine metals from virgin ores. The utilization of these growing metal stocks through recycling is expected to be an important source for future metal supply. Graedel et al. (2011) conducted a global study on metal recycling rates and concluded that most metals have too low recycling rates regarding their importance in crucial new technologies (for instance battery for electric cars), with significant potential for improvement. However, regarding for instance copper, the recycling input rate is continuously decreasing since 2011 (ranging from 36% in 2011 to 29% in 2016), while the secondary refined production is quite stable over the same period (ICSG, 2018). This shows that there is still room for improvement. In that context, the objective of this work is to propose a management strategy that could be implemented to support the deployment of a circular economy.

French copper cycle has been chosen as an application case because of copper importance in today's world as the third metal

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Nomenclature

A	Anode (furnace)
ADEME	French Environment and Energy Management Agency
BRGM	French Geological Survey
C&D	Construction and Demolition Waste
DTB	Direct-to-blister (flash smelter)
EC	Energy Cost
Elec	Electric (furnace)
EI	Environmental Impact
ELV	End-of-Life Vehicles
ER	Electrolytic Refinery
GA	Genetic Algorithm
GHG	GreenHouse Gas
I&HW	Industrial and Hazardous Waste
LCA	Life Cycle Assessment
LGS	Low Grade Scrap
LSXEW	Leach-Solvent eXtraction-ElectroWin
MSW	Municipal Solid Waste
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer NonLinear Program
NOR	Noranda (furnace)
OUT	Outukumpu (flash smelter)
PS	Pierce Smith (converter)
RC	Refined Copper
SKS	Shuikoushan (bath furnace)
SS	Sewage Sludge
TEN	Teniente (furnace)
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
WEEE	Waste from Electrical and Electronic Equipment

used in the world (after iron and aluminum) and used in many areas (Muchova et al., 2011). The case of copper is also very interesting because of the important available copper deposit. Indeed, it is estimated that 80% of the copper extracted since prehistory is still in use, immobilized in construction (55%), infrastructure (15%), industry (10%), transport (10%) and equipment (10%), with an average 30-year use duration (from a few years for electronic equipment until hundreds years for buildings) (SCF, 2019). However, in 2016, about 29% of the world copper consumption came from recycled wastes while only about 30% of available copper wastes have been recycled (ICSG, 2018) (against nearly 36% in 2014 (ICSG, 2016)). France does not take part in most of copper cycle, in particular in metallurgy and refining, but has an important copper primary processing industry from refined copper and is an important producer of semi-finished products (SCF, 2019). Moreover, Gie et al. (2010) showed that, in 2008 in France, most of copper losses occurred during the waste management step, as France only recycled 3.5% of collected wastes and exported most of the remainder. In 2014 in France, according to an ADEME report (Bio by Deloitte, 2017), 183 *kt* of copper were collected in the waste and 56 *kt* of copper in waste were imported, while 197 *kt* were exported and 42 *kt* were recycled by fusion, which leads to a recycling input rate of 17% (against 39% in 2011). This high exportation flow is composed of complex wastes that cannot be treated in France with the existing facilities, adapted only for high grade scraps. Please note that a high variability of the recycling input rate has also been highlighted due to data uncertainties and confirms that copper waste situation in France has been observed as quite stable since 2009.

According to Giurco and Petrie (2007), innovative technologies have only a limited role on the reduction of carbon footprint of copper, and the optimization of copper management should cover both technology and flowrate management optimization. To reach a more sustainable system, the management of copper recycling processes is addressed in this work.

For this purpose, a cartography of the current French copper cycle has been carried out in a previous work (Bonnin et al., 2013). This cartography has shown that most of copper losses occur during the waste treatment step. Indeed, most of French copper scraps are exported or discarded, while only a low highly concentrated fraction is recycled. Following this observation, a second study has been conducted that focused on copper scrap recycling processes (Bonnin et al., 2015). This second study led to the proposal of a mathematical formulation that aimed to optimize copper scrap management and that was illustrated by the choice of the optimal process for the recycling of printed wiring board. This previous study also showed the interest of using genetic algorithms (GA) to solve this kind of optimization problems. The idea here is to use the results obtained in these two first works to propose a superstructure that encompasses the French copper cycle model and the scrap management optimization method to develop an optimization methodology for integrated resource management. The model formulation is generic enough so that data can be easily updated if necessary. Yet as aforementioned, the copper situation in France is fairly stable.

This paper presents firstly an inventory of the work carried out on copper mapping, management, recycling and environmental impact assessment 2.

Then the formulation and implementation of the optimization problem is described (part 3): a copper management superstructure is proposed, including as decision variables all possible management options. The specific parameters to this case study are specified: definition of model input data and of decision variable bounds. The involved algorithm and the formulation of the problem are developed. The choice of software and program structure are described. Finally, single and multi-objective optimization are conducted to determine a compromise solution.

Lastly, section 4 provides a critical analysis and perspective to go further.

2. Literature review

2.1. Copper in literature

Many studies have already focused on copper. This part presents some of the main works regarding the mapping of copper flow, the extraction and mining management assessment and the production and recycling processes evaluation.

2.1.1. Copper flow cartography

A huge amount of works has been performed on the assessment of copper flow, whether at city, country or world scale. This issue has been more widely explored in our first work (Bonnin et al., 2013), but some of the main and more recent works are still worth being presented here.

“The contemporary European copper cycle” study (Spatari et al.,

2002) can probably be considered as one of the most significant works, and the methodology that has been carried out has then been adopted for developing similar studies in Asia (Kapur et al., 2003), Africa (van Beers et al., 2003), Latin American and Caribbean (Vexler et al., 2004), China (Guo and Song, 2008), United Kingdom (Jones, 2009), Brazil (Tanimoto et al., 2010), etc. as well as for studies on other chemicals (for instance silver (Lanzano et al., 2006)). These studies used the material flow analysis methodology that gives a picture of the situation at a specific time.

More recently, some authors have emphasized the importance of dynamic analysis that allow to define indicators and draw tendencies that can be used for decision making (Glöser et al., 2013; Soulier et al., 2018a,b; Pfaff et al., 2018), etc.). All these studies address in particular the issue of secondary copper availability, which can be calculated thanks to dynamic analysis by combining the in-use stocks with end-use lifetime assumptions, and the recycling efficiency, that varies a lot from one country to the other. For instance, France has a good copper waste collection rate but exports nearly all of it, while China recycles a high amount of imported copper waste but has a relatively low domestic recycling efficiency.

2.1.2. Extraction and mining

The long term availability of copper being of crucial importance for our lifestyle, many studies focus on the extraction and mining issues. A paper from Northey et al. (2014) on the modeling of future copper ore grade, whose expected decline will have important impacts on cost and environmental impacts of copper extraction, is a good example of these issues. On a complementary topic, Memary et al. (2012) conducted time-series life cycle assessment to determine environmental impacts of copper mining and smelting in Australia, and showed that LCA models are interesting tools to help decision makers choose technology and energy strategies in the mineral sector. Finally, Govindan (2015) reviewed eleven paper dealing with multi-criteria decision making or operations research in the implementation of sustainability in mining and minerals sector, and concluded that these new tools and techniques are of high interest for future research in sustainable mining.

2.1.3. Production and recycling processes

Once again, studies on copper production and recycling process are widely present in literature. This issue was explored in more details in Bonnin et al. (2015), and those with specific focus on the work explored here are recalled for the sake of clarity.

In an environmental impact assessment perspective, Norgate et al. (2007) proposed an important review of metal production processes, including copper, and performed LCA for comparative purpose. Similarly, Farjana et al. (2019) carried out a life cycle analysis of copper-gold-lead-silver-zinc beneficiation process that shows the interests and limits of recycling regarding environmental impacts and that gives keys for comparison with primary production.

However, most of the works on copper recycling focus on Waste from Electrical and Electronic Equipment (WEEE) with the highest copper content and ignore other wastes. Some interesting works on WEEE recycling optimization can be cited: Johansson and Luttropp (2009); Kasper et al. (2011); de Souza et al. (2016); Dias et al. (2018); Meester et al. (2019).

2.1.4. Copper literature review conclusion

In these studies, depending on the objectives, mono or multi-criteria optimization strategies are sometimes used to find the best compromise between costs, environmental impacts, risks, etc. Multicriteria strategies used in these different works proved their efficiency to solve complex decision making problems. For instance, Minciardi et al. (2008) proposed a strategy for the optimization of solid waste flows treatment at urban scale. In another field of application, Sharif and Hammad (2019) showed the interest of coupling life cycle assessment and multicriteria optimization for building renovation. However, there is no study aiming at performing a multicriteria optimization of the whole cycle of a given resource. Indeed, the optimization of a resource management is not only a multiobjective problem (aiming at minimizing simultaneously cost, energy consumption, environmental impacts, etc.), but also a mixed problem with many continuous (such as flowrates) and integer variables (for example the choice between different process alternatives) (Giurco, 2009). The aim of this work is to propose a strategy to optimize the copper cycle encompassing resource supply to waste management, considering both environmental and economic issues with a life cycle approach. This is consistent with the works of Jeswani et al. (2010), Petrillo et al. (2016) and many others that show how Life Cycle Assessment method can be improved by being combined with economic studies. A review that showed the interest of coupling economic models and environmental assessment methods has been proposed by Beaussier et al. (2019).

2.2. Multicriteria optimization strategy and support decision making tool

Resource consumption leads not only to depletion of abiotic resources, but also to indirect impacts on health and environment such as energy consumption, pollutant emission, etc. Moreover, resource extraction is expensive. The objective is to mathematically model all the copper flows and to identify the decision variables that can act as key drivers to improve resource management.

In a sustainable development perspective, economic, environmental and social criteria have to be taken into account. The difficulty is that each of these sustainable pillars might be evaluated by a large amount of indicators (Milutinovic et al., 2014). For instance, environmental impacts can be estimated considering pollutants emission, waste generation, energy consumption, etc. Each impact could also be estimated with many “sub-indicators”: for instance, to help policy decision making on energy management, the International Atomic Energy Agency (2005) proposed a set of about 30 “Energy Indicators for Sustainable Development”. Furthermore, considering environmental impacts, a life cycle assessment (LCA) leads to 5 to about 20 different impacts (global warming potential, toxicity, eutrophication, resources depletion, etc.), which can also constitute a set of sub-indicators for the environmental impact evaluation.

The complexity of the decision making process increases yet with the number of decision criteria. How could an optimal compromise solution be found when more than ten antagonist objectives have to be optimized simultaneously? To limit complexity, different works on specific waste management optimization have adopted to work on a limited number of optimization criteria. Minciardi et al. (2008) have chosen four decision variables for the optimization of solid waste flows: economic costs, unrecycled waste, sanitary landfill disposal and environmental impact. Zaman (2016) attempted to measure the waste management system efficiency in different countries with a new indicator, i.e. the Zero Waste Index (ZWI). The ZWI accounts for the potential amount of virgin material that can be offset by recycling, minimizing energy and water consumption, as well as greenhouse gas (GHG) emissions, by offsetting virgin materials and recovering energy from waste. Another set of indicators, including management costs and reuse time span as well as different objectives of economy, perceived risk and environmental impact, has been used by Ahluwalia and Nema (2007) for optimizing computer waste management.

Regarding the tool choice, the model developed here encompasses the formulation of the copper scrap management model proposed in Bonnin et al. (2015): optimization and decision making strategies use the same tools, which are the Genetic Algorithm (GA) for the multiobjective optimization and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) decision support tool. The interested reader will find more information on multiobjective optimization in Mahdi et al. (2018); Qu et al. (2018) literature reviews and on multi-criteria decision-making in Mardani et al. (2017); Govindan et al. (2015); Kumar et al. (2017) literature reviews.

3. Problem formulation and implementation of the optimization process

3.1. Choice of the criteria

Considering the reported works in the literature review section, it was decided for this study to focus only on environmental and economic objectives, which can be more easily and objectively estimated than social impacts. The efficiency of the resource management system has thus been assessed by four criteria:

- economic efficiency is evaluated by calculating the costs of the resource cycle;
- environmental impacts are determined via:
  - energy consumption;
  - greenhouse gases emissions;
  - abiotic resources depletion, taken into account by calculating copper losses.

For each of these criteria, the total impact is calculated considering waste collection (either selective or not), sorting and disposal (either landfilling or incineration), as well as scrap recycling and import/export flows.

3.2. Mathematical formulation of the model

Fig. 1 presents the superstructure that can be used for the management optimization of any natural resource that embeds all the options that can be explored by the solution algorithm. Two constraints are considered in this model formulation: the former one involves the satisfaction of the demand in refined copper and in refined alloys (both are estimated from copper use), and the latter involves a fixed input data set based on the waste deposit. These parameters can be determined from national statistics as well as from company and association data reports: this has been the core of another study (Bonnin et al., 2013). All the other flows are free and thus considered as decision variables.

The decision process starts with the total amount of produced waste; then the decisions are made according to the waste flow circulation (Table 1):

- Wastes can be collected (wholly or partly) either selectively or not (d1). It is assumed that non-selectively collected waste are landfilled;
- Selectively-collected wastes are sorted into six streams: construction and demolition wastes (C&D), End-of-Life Vehicles (ELV), Waste from Electric and Electronic Equipment, Municipal Solid Waste (MSW), Sewage Sludge (SS) and Industrial and Hazardous Wastes (I&HW). If discarded, MSW, SS and I&HW can be either landfilled or incinerated (d2), while ELV, WEEE and C&D can only be incinerated (because of French legislation);
- It is possible to import mixed wastes (d3), but imported waste are assumed to be recycled, thus they are sorted and mixed with selectively collected wastes;
- Then the decisions concerning each stream are made independently from each other: it is possible to import or export a specific stream (d4-d9), then for each remaining stream there is a choice between discarding, recycling and sorting (d10-d15);
- Sorted streams are divided into six scrap categories: No.1 scrap (>99% *Cu*), No.2 scrap (88–99% *Cu*), low grade scrap (LGS) (10–88% *Cu*), alloys and remaining scrap (<10% *Cu*). Each scrap stream can either be discarded or recycled (d20-d23). Waste streams that are recycled without being sorted are mixed with LGS or remaining scrap depending on their copper content;
- Scrap streams can also be imported or exported (d16-d19), but as for mixed wastes, imported scraps are assumed meant to be recycled and can thus not be discarded;
- Then all recycled scrap streams enter the recycling flowsheet construction process: it is possible to import copper from primary industry (concentrate, mate, etc.; d27-d29) and then the flowsheet is selected (d24-d26). It was assumed that, on the lifetime of the facilities, capital construction costs are insignificant compared to running costs;
- Finally refined copper and alloys importation or exportation flowrates are calculated in order to meet the demand.

It has to be highlighted that the recycling of copper scrap has been an important issue of this work: an innovative recycling flowsheet construction methodology has been developed and presented in detail in Bonnin et al. (2015). The method aims at finding all the possible combinations of process, i.e. flowsheets, that can be used to transform a copper scrap into refined copper, associated with their costs, energy consumption, greenhouse gases emissions and copper losses.

Two main routes exist for copper recycling: the pyrometallurgical and the hydrometallurgical technologies. The pyrometallurgical alternative can be divided into six steps from ore or low grade scraps to refined copper: pre-treatment, smelting, converting, fire refining, electrorefining and smelting for form casting. Nine processes can be used, alone or associated with each other, for these steps, depending on the recycled metal characteristics: anode furnace (A), direct-to-blister flash smelter (DTB), electric furnace (Elec), electrolytic refinery (ER), Noranda furnace (NOR), Outukumpu flash smelter (OUT), Pierce Smith converter (PS), Shuikoushan bath furnace (SKS) and Teniente furnace (TEN). The hydrometallurgical method is based on leach-solvent extraction-electrowin (LSXEW) technology and is described here as a unique step from scrap to refined copper. More details on these ten processes are given by Suljada (2001). For readability reasons, Fig. 1 only shows the different steps of the pyrometallurgical process. It would be similar with hydrometallurgical process but simpler as all six steps of the recycling process would be condensed in one process. The best flowsheet (that can embed one to five of the 10 cited processes) for a specific kind of scrap is determined based on data such as copper, lead, iron, zinc and tin contents, scrap sized, moisture, etc.

Finally, as shown in Table 1, the whole formulation involves 47 variables, either continuous (imports minus exports, rate of selective collection, etc.) or integer (choice between processing, sorting and discarding, etc.). Moreover, mainly because of the recycling process construction formulation, the problem is also nonlinear, so that a Mixed-Integer NonLinear formulation of the problem is involved (Bonnin et al., 2015).

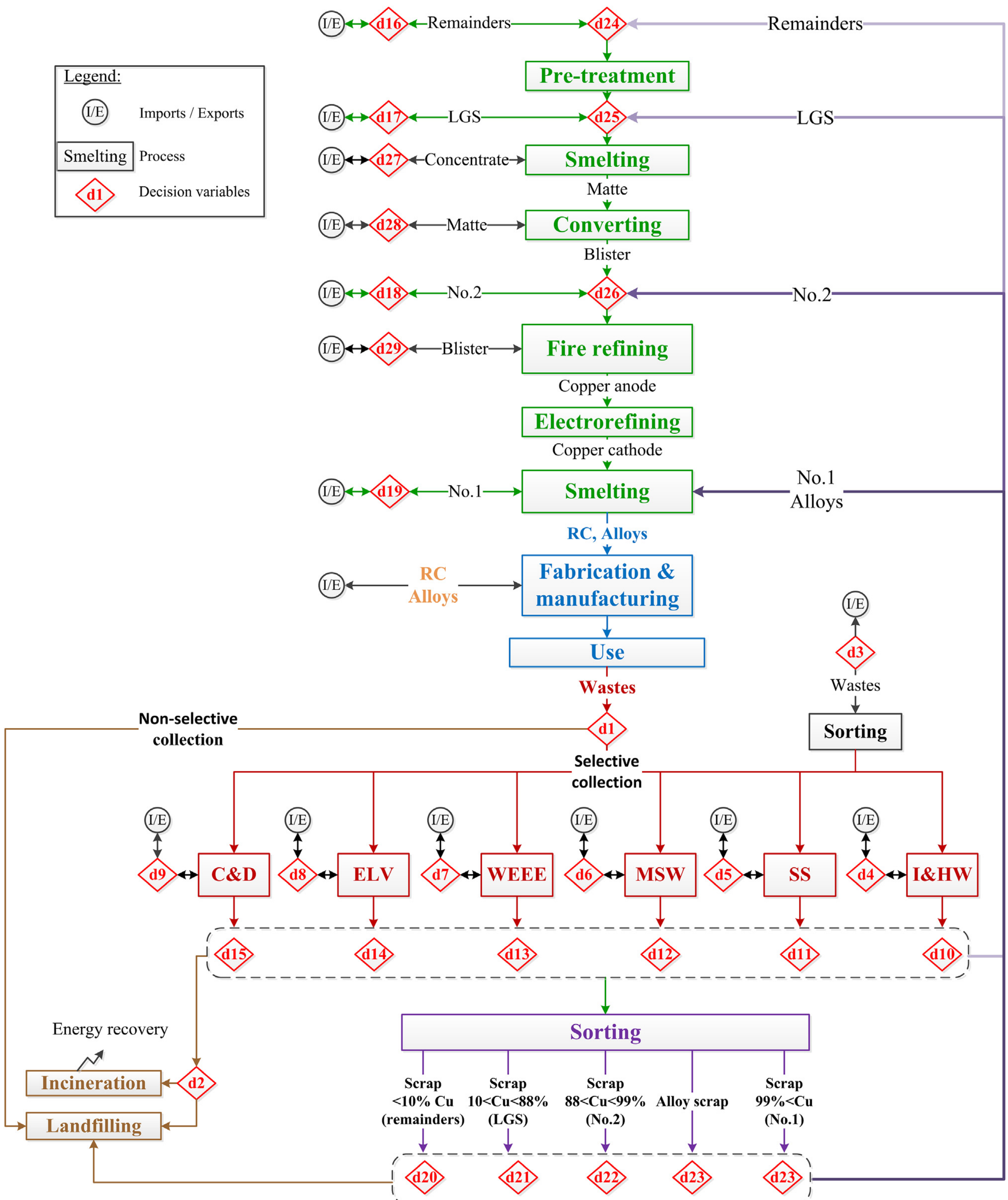

Fig. 1. Superstructure of copper processing pathways.

Table 1
Decision variables for problem formulation.

di	Variable	Definition domain	Variable type
d1	Rate of selectively collected scrap	$[0\,;1]$	Continuous
d2	Rate of landfilled MSW, SS and I&HW (the remainder being incinerated)	$[0\,;1]^3$	Continuous
d3	I-E of mixed waste (kt/an)	$\mathbb{R}$	Continuous
d4	I-E of I&HW (kt/an)	$\mathbb{R}$	Continuous
d5	I-E of SS (kt/an)	$\mathbb{R}$	Continuous
d6	I-E of MSW (kt/an)	$\mathbb{R}$	Continuous
d7	I-E of WEEE (kt/an)	$\mathbb{R}$	Continuous
d8	I-E of ELV (kt/an)	$\mathbb{R}$	Continuous
d9	I-E of C&D (kt/an)	$\mathbb{R}$	Continuous
d10	Choice between P, S and D for I&HW	$\{1;2;3\}$	Integer
d11	Choice between P, S and D for SS	$\{1;2;3\}$	Integer
d12	Choice between P, S and D for MSW	$\{1;2;3\}$	Integer
d13	Choice between P, S and D for WEEE	$\{1;2;3\}$	Integer
d14	Choice between P, S and D for ELV	$\{1;2;3\}$	Integer
d15	Choice between P, S and D for C&D	$\{1;2;3\}$	Integer
d16	I-E of remainder scrap (residuals) (kt/an)	$\mathbb{R}$	Continuous
d17	I-E of low grade scrap (LGS) (kt/an)	$\mathbb{R}$	Continuous
d18	I-E of high content scrap (No.2) (kt/an)	$\mathbb{R}$	Continuous
d19	I-E of pure scrap (No.1) (kt/an)	$\mathbb{R}$	Continuous
d20	Choice between P and D for residuals	$\{0;1\}^6$	Binary
d21	Choice between P and D for LGS	$\{0;1\}^6$	Binary
d22	Choice between P and D for No.2 scrap	$\{0;1\}^2$	Binary
d23	Choice between P and D for No.1 scrap and alloys	$\{0;1\}^6$	Binary
d24	Flowsheet choice for residuals	$\mathbb{N}^*$	Integer
d25	Flowsheet choice for LGS	$\mathbb{N}^*$	Integer
d26	Flowsheet choice for No.2 scrap	$\mathbb{N}^*$	Integer
d27	I-E of copper concentrate (kt/an)	$\mathbb{R}$	Continuous
d28	I-E of copper matte (kt/an)	$\mathbb{R}$	Continuous
d29	I-E of blister (kt/an)	$\mathbb{R}$	Continuous

Legend: P: processing - S: sorting - D: discarding - I-E: imports minus exports.

3.3. Model parameters

As seen in the definition of the superstructure of the problem, the objective is to determine the set of the decision variables (47) that optimizes simultaneously costs, environmental impacts, energy consumption and losses due to copper management during a year, to meet demand without importing refined copper or alloys from primary industry. The problem formulation is based on the determination of the model input parameters (demand for refined copper and alloys, waste deposit), as well as bounds between which the decision variables may vary.

3.3.1. Input parameters

The input parameters of the model have been taken from Bonnin et al. (2013), in which a cartography of the copper cycle in France from 2000 to 2009 is presented. This study showed that the copper amount contained in the waste has been fairly stable since the early 2000's: around 300 $kt_{Cu}/year$, contained in a total amount of waste of about 192,000 kt, with more than two thirds of copper embedded in waste from electrical and electronic equipment (WEEE).

Moreover, as previously mentioned, the recycling flowsheet construction requires, in addition to copper content, iron, lead, tin and zinc concentrations, as well as the quantity of each type of scrap that can be extracted by sorting the wastes. Some characterizations were performed using a compilation of data from ADEME (French Environment and Energy Management Agency) and BRGM (French Geological Survey) reports, as well as reports on the different types of waste (Richer et al., 2001; Bremond, 2008; ADEME, 2019; Fangeat, 2009; Brahmst, 2006) and are presented in Tables 2 and 3.

Table 2
Composition of the different categories of waste.

	WEEE	ELV	C&D	I&HW	MSW	SS
Copper	13%	2.5%	0.07%	0.02%	0.0065%	0.037%
Iron	43%	62.1%	0.36%	10.00%	0%	0%
Zinc	3%	1.0%	0.35%	0.02%	0.0301%	0%
Lead	3%	1.3%	0.35%	0.02%	0%	0%
Tin	1%	1.0%	0.35%	0.02%	0%	0%
Residuals	37%	32.1%	98.52%	89.92%	99.9634%	99.963%

Table 3
Scrap content in the different categories of waste.

	WEEE	ELV	C&D	I&HW	MSW	SS
No.1	1%	0.50%	0.001%	0%	0%	0%
No.2	1%	0.05%	0%	0%	0%	0%
LGS	15%	5.00%	0.080%	0.01%	0.005%	0.1%
Alloys	5%	0.50%	0.010%	0%	0%	0%
Residuals	78%	93.95%	99.909%	99.99%	99.995%	99.9%

Regarding demand, flow modeling has shown that between 2000 and 2009 the difference between the amounts of refined copper imports and exports decreased from about 580 kt in 2000 to 375 kt in 2008. In addition, France is a major importer of copper in finished and semi-finished products. The amount of imported and exported copper in finished and semi-finished products has been assumed to be constant. This hypothesis could be questioned but has been adopted because of the lack of data. Thus, recycling is only used to meet the refined copper demand, which was set at 400$kt/year$.

Regarding alloys, the amount used in France by the process industries is not known in detail, which is why the demand was set equal to the amount of alloys present in the finished products manufactured in France, i.e. about 100 $kt/year$. It should be highlighted that many types of alloys are used in various sectors, and an accurate counting would be very difficult to drive. The alloys have been considered in this study as only one type of scrap containing about 60% of copper, which is the concentration in many brasses and bronzes that are the most commonly used alloys.

As previously mentioned, France recycles today about 50 *kt* per year of high grade scrap. Nearly all of it is imported scrap, while most of copper waste collected in France is exported. Only one company can recycle No.2 scrap, three companies can only treat No.1 scrap, and about ten companies use high quality recycled copper in their semi-products and products production process (Jérôme Betton, 2014). To test the potential of the optimization strategy, the optimization process has been initialized with a "blank" page and no information on the current used technologies was implemented. Moreover, industrial confidentiality makes this kind of information difficult to obtain.

3.3.2. Variable boundaries

As presented in Table 1, the problem consists of 18 continuous variables, 9 integer variables and 20 binary variables.

For the binary variables, which represent the choice between recycling and disposal for each scrap from each waste, no bound is fixed.

For integer variables, the bounds depend of the variable type:

- the six variables concerning the future of each waste category can vary from 1 to 3: if $di = 1$ the category is sent directly to recycling, if $di = 2$, it is sorted and if $di = 3$, it is discarded.
- the selection of three recycling flowsheet choice variables returns *di*, the index of the flowsheet adopted and therefore varies between 1 and the number of useable flowsheet for each scrap. The number of flowsheets was calculated with the method mentioned in part 3 and described in Bonnin et al. (2015): 7 flowsheets can be used for No.2 scrap, 127 for LGS and only one for the remaining scrap, which simplify the problem by removing one integer variable. The problem includes finally 46 variables.

Regarding continuous variables, there are also two categories: those representing a sharing rate, which are between 0 and 1, and those representing the difference between imports and exports, defined on \mathdsR.

Concerning the seven "sharing rate" variables used, to find treatment solutions consistent with the French situation, given the compositions and characteristics of WEEE, ELV and C&D, it was decided to prohibit incineration.

Finally, for continuous "imports minus exports" variables, bounds must be defined. For lower bounds, i.e. export limitations, the maximum amounts that can be exported of each waste or scrap were calculated. For example, the maximum amount of household waste (MSW) that can be exported is calculated by assuming that all waste is collected selectively and imports of mixed waste are at their maximum (remembering that, by definition, imported mixed waste are sorted and divided into the six waste categories). The quantity of available MSW is then calculated and this sets the maximum amount that may be exported. Regarding the upper limit, i.e. the highest imports, its value has been fixed so that the maximum imports of a flow is sufficient to cover the demand for refined copper, with a maximum set at the amount of (each) waste produced in France.

Table 4 summarizes the bounds used for the decision variables corresponding to imports minus exports of each category of waste or scrap ("*di*" indexes correspond to those presented in Fig. 1).

The model formulation offers a superstructure that can be adapted to different situations in different countries. For all the other streams, flowrates are calculated in accordance with what is presented in part 3 and with the data presented in Appendix A.

Table 4
Bounds of imports and exports decision variables.

di	Variable	Lower bounds (kt/an)	Upper bounds (kt/an)
d3	I-E of mixed waste	−192,000	192,000
d4	I-E of I&HW	−204,288	102,144
d5	I-E of SS	−1920	960
d6	I-E of MSW	−62,976	31,488
d7	I-E of WEEE	−3072	1536
d8	I-E of ELV	−3456	1728
d9	I-E of C&D	−108,288	54,144
d16	I-E of remainder waste (Residual)	−96,341	192,000
d17	I-E of low grade scrap (LGS)	−1119	1600
d18	I-E of high grade scrap (No.2)	−49	416
d19	I-E of pure scrap (No.1)	−51	400
d27	I-E of copper concentrate	0	1600
d28	I-E of matte	0	548
d29	I-E of blister	0	417

Legend: I-E: imports minus exports.

3.4. Impact evaluation

As detailed in the formulation of the problem, imported flows intended *a priori* to be recycled. The following assumptions have been adopted:

- mixed waste imports are necessarily sorted into the six categories of waste selective collection;
- waste imported by category is mixed with flows from selective collection and from mixed wastes sorting;
- imported scrap, concentrate, matte and blisters are necessarily sent to the recycling process and are mixed with sorted scrap sent for recycling (depending on their content);
- if a scrap coming in the recycling chain cannot be treated by any flowsheet, it is discarded.

Then the four objective functions (Costs, GHG Emissions, Energy consumption and Losses) are calculated according to the following equations (Eqs. (1)–(4)), using data presented in Appendix A:

$$C_{Total} = C_{recycling} + C_{disposal} + C_{sorting} + C_{I-E} \tag{1}$$

$$EI_{Total} = EI_{recycling} + EI_{disposal} + EI_{sorting} + EI_{I-E} \tag{2}$$

$$NRJ_{Total} = NRJ_{recycling} + NRJ_{disposal} + NRJ_{sorting} + NRJ_{I-E} \tag{3}$$

$$L_{Total} = L_{disposal} + L_{recycling} + L_E \tag{4}$$

with:

- C_{Total}: total costs in monetary units;
- $C_{recycling}$: costs related to recycling processes, calculated from energy and material consumption (these costs do not take into account the investment costs, like infrastructures, etc.);
- $C_{disposal}$: costs of waste disposal (landfill or incineration) (Andrup et al., 2011);
- $C_{sorting}$: costs of sorting waste (to extract scraps);
- C_{I-E}: costs of imports and exports.
- EI_{Total}: total environmental impacts, simplified to GHG emissions, expressed in equivalent CO_2;
- $EI_{recycling}$: impacts related exclusively to recycling processes, calculated from the energy consumption and material processes with impact factors extracted from SimaPro software and using the database EcoInvent (Classen et al., 2007);
- $EI_{disposal}$: impacts associated with waste disposal (landfill or incineration);

- $EI_{sorting}$: impacts associated with waste separation (to extract scraps);
- EI_{I-E}: impacts attributed to imports and exports (copper, waste, etc.);
- NRJ_{Total}: total energy consumption;
- $NRJ_{recycling}$: processes energy (and materials) consumption;
- $NRJ_{disposal}$: energy consumption linked to waste disposal;
- $NRJ_{sorting}$: energy consumption related to waste sorting (to extract scraps);
- NRJ_{I-E}: energy consumption attributable to imports and exports.
- L_{Total}: total losses of copper;
- $L_{disposal}$: copper contained in the categories of waste neither sorted or sent directly to recycling, or in disposed scraps;
- $L_{recycling}$: copper contained in scraps from recycling processes (W_1 and W_2);
- L_E: copper contained in exported waste or scrap.

3.5. Optimization strategy

Many different optimization algorithms can be used depending on the model formulation. According to a previous study dedicated to the optimization of the recycling of copper waste (Bonnin et al., 2015), genetic algorithms have been identified as one of the most suited methods for addressing multi-criteria, mixed and non-linear problems, despite their known limits regarding computational time and absence of convergence properties for monobjective optimization problems. The analysis of available optimization methods led us to choose a genetic algorithm from MULTIGEN library, developed by Gomez (2008) and written in VBA with Excel® interface. The criteria that have to be optimized were calculated using Matlab® software.

A function called "*optimization*" was written to calculate the flowrates in each stream, evaluate the impacts associated with these flows and determine the amount of recycled copper, copper losses, etc., all depending upon the decision variables. The code is too long to be included here but it follows the process described in part 3.2 and Fig. 2 presents the architecture of the Matlab® program developed. The Matlab® function *optimization* was converted using the MATLAB Builder™ EX supplement into Excel® coding, so that the NSGA II Continuous Mixed-Integer-Boolean algorithm from MULTIGEN library can be used.

In a first step, monobjective optimizations have been performed for each criterion, in order to analyze their behavior. This allows to study the possible antagonism of the criteria and compare the decision variables to be optimized. If some criteria are redundant, it will be possible to reduce their number in the following multiobjective optimization procedure.

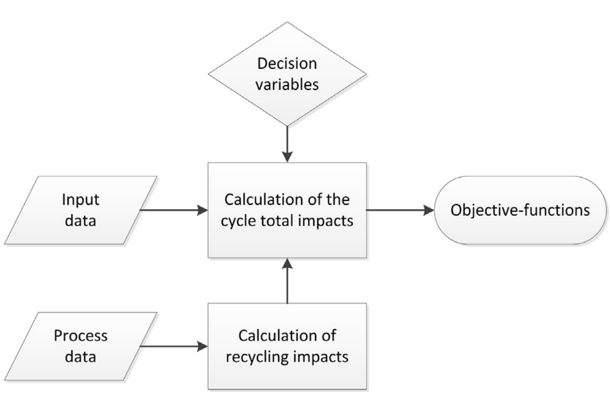

Fig. 2. Architecture of the impact calculation Matlab® program.

Table 5
Parameters used for the genetic algorithm.

Parameter	Value
Population size (= 20× number of variables)	920 individuals
Number of generations (= 2× number of individuals)	1840
Crossover probability	0.9
Mutation probability	0.5

As recommended by Gomez (2008), the genetic algorithm NSGA-II Mixed-Integer-Continue Boolean is used independently for each of the objective functions with the parameters presented in Table 5.

4. Results and discussion

Each function has been minimized by keeping free the other functions and setting the constraint relative to imports of refined copper and alloys at 0. The results are summarized in Table 6: each row corresponds to the monobjective optimization of the criterion mentioned in the first column, and the other columns give the costs, environmental impacts, energy consumption, copper losses and export flows of refined copper and alloys obtained with each monobjective optimization (the value in bold being the minimized criterion).

The four rows present quite different results: depending of the minimized criterion, the cost varies from 21 to 58 $G€/an$, environmental impacts from 35 to 103 $Mt_{eq_{CO_2}}/an$, energy consumption from −41 (production of 41 TWh/an due to waste incineration) to 148 TWh/an and copper losses from 38 to 302 kt/an. Moreover, the values of the exported flows of refined copper and alloys are clearly different for each optimization run, highlighting that copper management strategy depends on the targeted criterion. Indeed, a more extensive study of the variables of decision proves that all four criteria are clearly antagonists with very different strategies obtained depending on the studied criterion. These results are presented in detail in the following paragraphs.

4.1. Monobjective optimization

4.1.1. Cost minimization

Cost optimization shows that minimum copper management costs could be 21 $G€/an$. The required strategy to reach this result is characterized by:

- a rate of selective collection of 100%;
- significant imports of copper from primary industry (concentrates, mattes and blisters), No.1 scrap, LGS and WEEE;
- sorting of the most concentrated copper waste (WEEE), direct recycling of ELV and SS and disposal of other waste (C&D, I&HW et MSW);
- recycling of all scrap categories;
- incineration of I&HW and MSW.

Fig. 3 shows this management strategy, the size of the arrows is proportional to the flow of copper.[1]

The high cost of refined copper can explain these results so that it is interesting to produce as much copper as possible to sell the overflow once the demand is satisfied. Thus, all waste and scrap with recycling costs lower than refined copper price are recycled.

[1] With the exception of imports of low debris flow concentrates and mattes that is too large in relation to others and is divided by two.

Table 6
Results of monobjective optimizations.

Minimized criterion	Costs (G/an)	EI ($Mt_{eq_{CO_2}}/an$)	Energy[a] (TWh/an)	Losses (kt/an)	Exp. RC (kt/an)	Exp. alloys (kt/an)
Costs	**21**	103	−15	162	1806	115
EI	31	**35**	148	302	0	11
Energy	30	94	**−41**	220	0	8
Losses	58	68	35	**38**	6	22

Legend: EI: environmental impacts - Exp.: exportation - RC: refined copper.
[a] Please note that negative value means that there is production of energy instead of consumption.

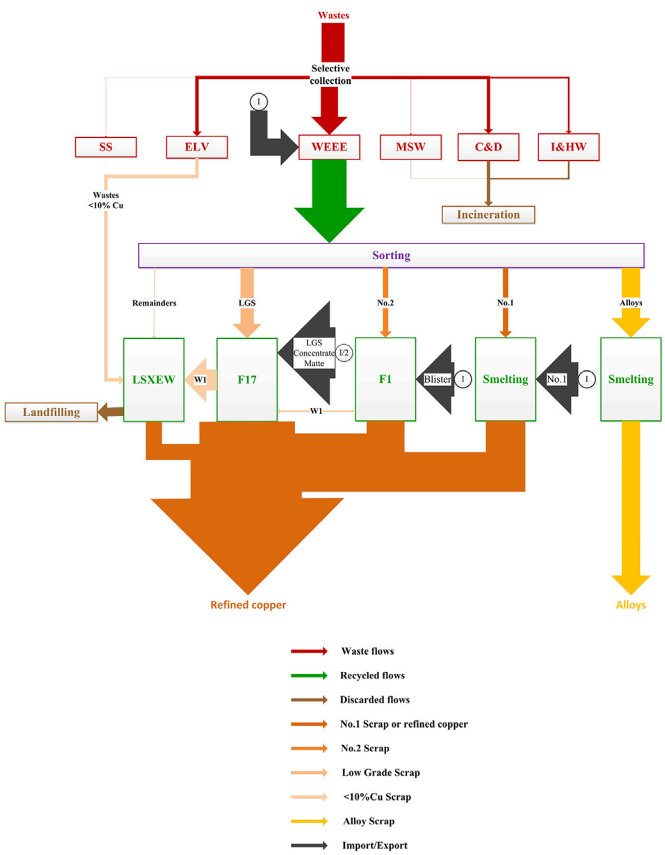

Fig. 3. Representation of flows in the cost minimization.

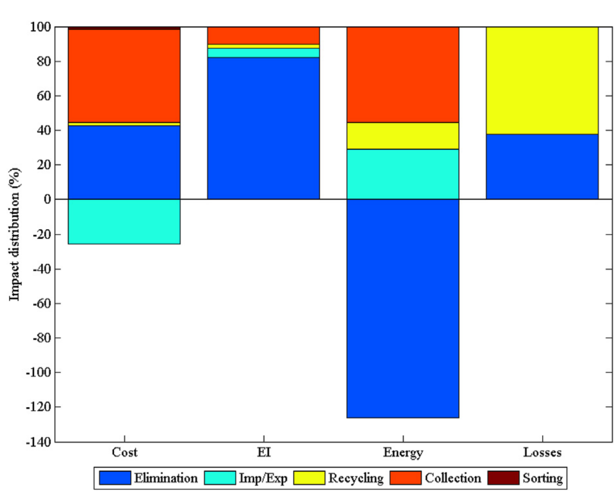

Fig. 4. Distribution of the different impacts at the cost minimization.

Others are incinerated (if possible, as explained in part 3.3.2) because, under the assumptions, it is the cheapest treatment through the sale of produced energy (see Appendix A.1).

With regard to recycling, no No.2 scrap import is involved to reach the minimum cost. No.2 scrap from WEEE is recycled with imported blister by a process comprising an electric furnace and an anode furnace. For LGS, a flowsheet consisting of three processes is used: a Teniente furnace, a Peirce-Smith converter and an anode furnace.

Fig. 4 presents the impact distribution between the different steps for each studied impact. The copper life cycle steps have been combined in five main stages: copper waste collection, recycling processes, waste sorting into scraps, elimination of wastes and scraps and import/export flows (sum of all flows, whatever they are.).

The collection and disposal of wastes are the most expensive steps, due to the very large flows involved. The remainder is due to recycling. The cost of waste sorting is insignificant here because only the WEEE are sorted, which represents a small amount. The exports of refined copper and sales cover about 20% of expenditures.

With regard to the other criteria, that are not optimized for this monobjective optimization run, the environmental impacts are approximately 3 times higher than their minimum (103 instead of 35 $Mt_{eq_{CO_2}}/year$) and are mainly due to waste incineration (I&HW, MSW and SS, which represents a large volume). Cost minimization leads to a small energy production through waste incineration. Energy consumption is divided between collection (50%), recycling (25%) and international trade (25%), but waste incineration produces so much energy than finally there is an energy gain rather than a consumption. Losses are shared equally between recycling and disposal. Indeed, the copper content of the waste disposed is very low, while large quantities of low copper are recycled.

4.1.2. Minimization of environmental impacts

The minimization of the environmental impacts leads to a strategy producing about 35 $Mt_{eq_{CO_2}}/year$. This requires (Fig. 5):

- a rate of selective collection of 100%;
- importing a small amount of WEEE and sorting and exporting all other waste;
- importing of copper from primary industry (mattes and blisters), recycled with scrap from WEEE.

These results are explained by the fact that, for exported waste, only transportation impacts were considered (once exported, it is not known whether the waste is recycled, discarded, etc.). These impacts are less important than those related to the disposal or recycling of waste: low grade waste are mainly exported. Only WEEE are fully preserved to be sorted and recycled. Copper from primary industry is imported to meet the constraints of non-importation of refined copper and alloys. This result shows the negative effects of taking into account only direct impacts: not charging impacts on exported waste makes it “cleaner” to export

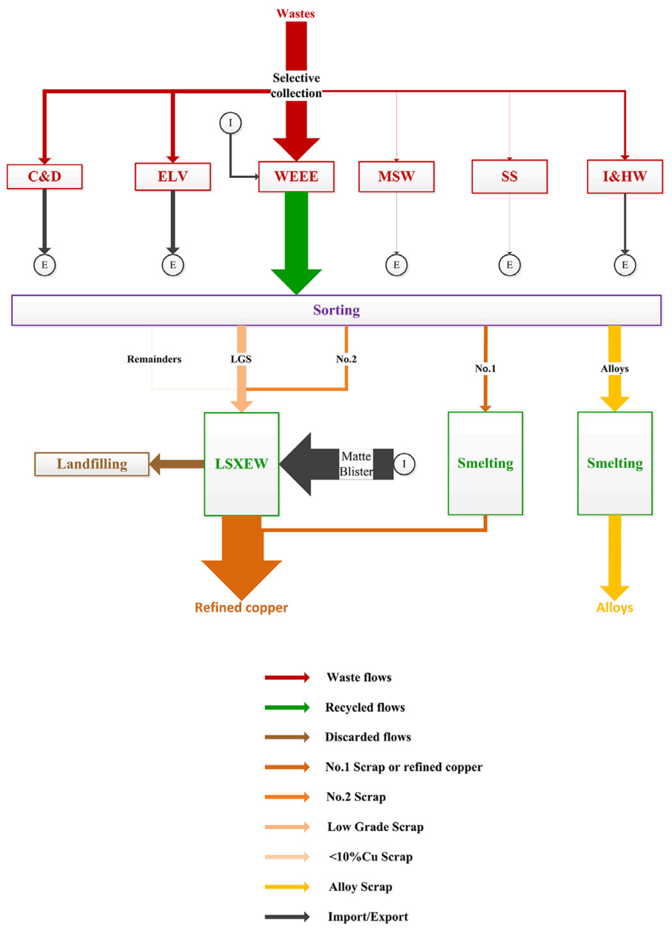

Fig. 5. Representation of flows when minimizing environmental impacts.

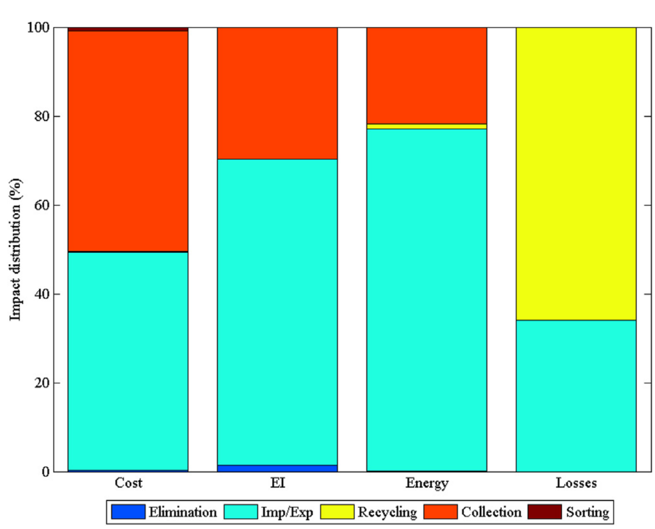

Fig. 6. Distribution of the different impacts when minimizing environmental impacts.

waste rather than recycling it. To mitigate this effect, the copper content in the waste exported was recorded as lost, so that, in the multiobjective problem, exportation is not favored.

Fig. 6 shows that the environmental impacts, costs and energy consumption are mainly due to imports and exports, which is explained by the large exported quantities. The second rank for these three criteria is due to collection, which also involves a

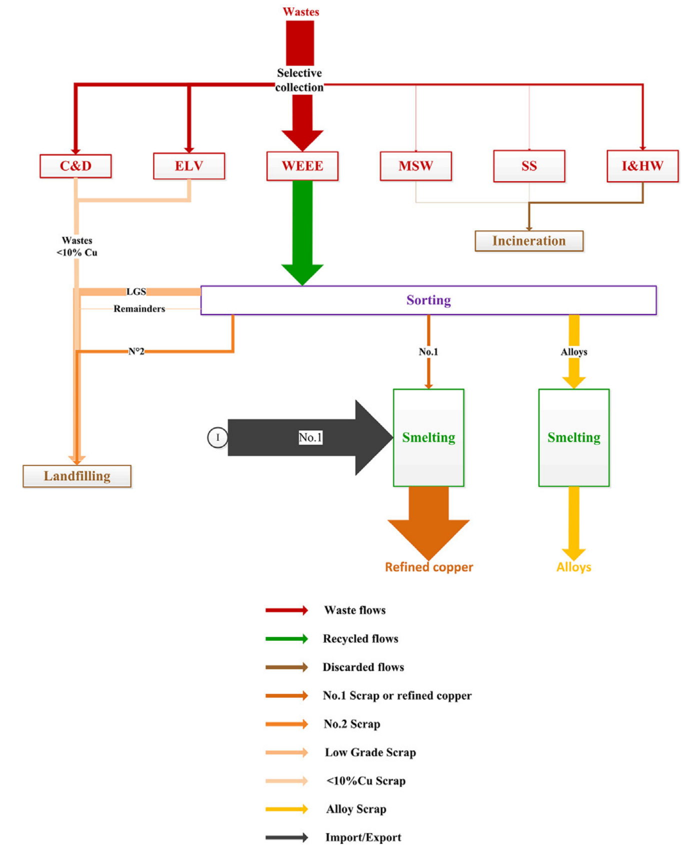

Fig. 7. Representation of flows during minimization of the energy consumption.

significant amount of waste. The small amount of waste recycled leads to negligible impacts to these three criteria.

Regarding losses, however, a substantial contribution is due to recycling. These huge losses can be explained by the fact that all recycled No.2 scrap and LGS, as well as matte and blister imported, are mixed and recycled as "residuals" (scrap containing 10% of *Cu*) using the hydrometallurgical process. Exported wastes also represent copper losses, but are less important because of their low content.

4.1.3. Minimizing energy consumption

Minimizing energy consumption actually leads to energy production of 41 *TWh*/*year*. This is explained by the assumption that the energy released during incineration of waste is recovered by electricity production.

The following parameters allow such a result (Fig. 7):

- a rate of selective collection of 100%;
- WEEE sorting and disposal of other waste;
- incineration of I&HW, disposal of MSW and SS;
- import of No.1 scrap to meet demand and recycling of No.1 scrap and alloys only.

Waste incineration produces energy, so the model proposes to incinerate as much waste as possible.

Since the recycling of other wastes and scraps consumes more energy than landfilling, only electronic waste is recycled in order to satisfy the constraint of non-importation of refined copper. The difference between the amount of copper contained in WEEE and demand is imported as No.1 scrap.

The study of impact sources, as shown in Fig. 8, shows that the

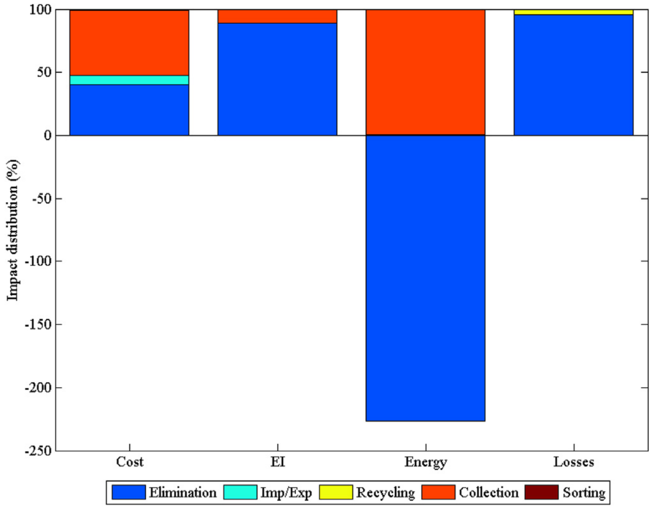

Fig. 8. Distribution of the various impacts during the minimization of the energy consumption.

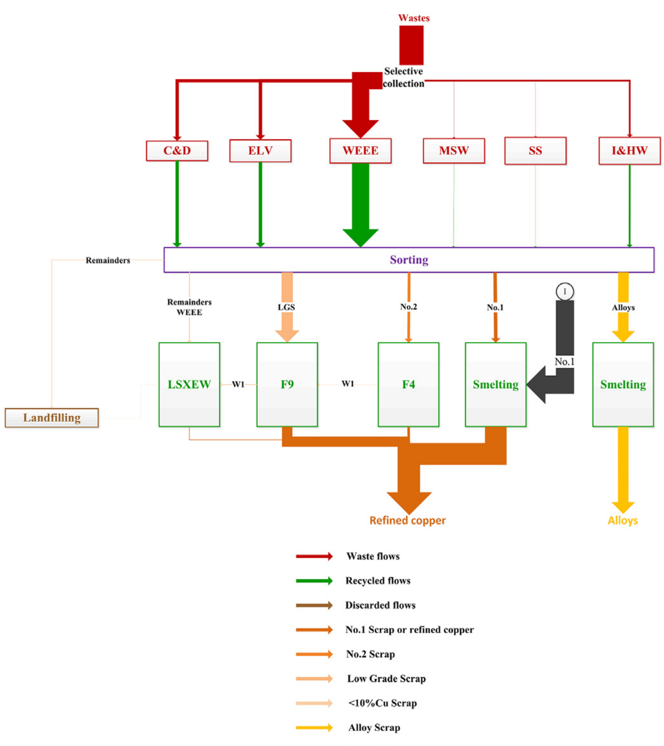

Fig. 9. Representation of flows when minimizing losses.

energy consumption (about 20 $TWh/year$) is almost entirely due to waste collection. The impacts on the environment and resource losses are mainly caused by waste disposal. Costs are mainly related to waste collection (55% of costs) and disposal (40% of costs).

4.1.4. Minimizing losses

The optimal value of losses flow, when considering this criterion alone, results in 40 $kt/year$ copper lost (about 10% of needs), which is far from being insignificant. This is explained by the fact that flows with very low copper content are important, and they cannot currently be recycled. Thus, minimizing losses requires the recycling of the largest possible amount of waste (Fig. 9):

- a rate of selective collection of 100%;
- sorting and recycling of all waste with a sufficient content (i.e. all scrap, except the remaining whose content is less than 0.03%);
- import of No.1 scrap, sufficient amount to meet demand.

It should be noted that the remaining scrap from the WEEE can be recycled by being mixed with new scrap from low grade scrap recycling.

As previously explained, having no information on the fate of exported wastes, only transportation impacts are allocated, thus favoring the exportation pathway. To mitigate this advantage, exports have been considered as losses, as they leave the considered cycle. Given these assumptions, the choice between export and disposal of waste that cannot be recycled does not impact this criterion. Similarly, import of No.1 scrap, for which recycling does not cause losses, may vary. Different values for these decision variables are therefore possible to reach this result, a variant without export is used for Figs. 9 and 10. With regard to recycling, two flowsheets can be used for No.2 scrap resulting in a similar result in terms of losses. A flowsheet consisting of an electric furnace and an anode furnace can be used, with the importation of a small amount of blister to slightly improve the copper content of the scrap. A similar flowsheet but with an electrorefining step is used in addition if no blister is imported. LGS are treated by means of an electric furnace, a Peirce-Smith converter and an anode furnace.

As it can be seen in Fig. 10 and 88% of the losses are due to the elimination of waste that can not be recycled, the remainder 12% being lost in the recycling process. In this configuration, the costs are mainly due to the large volumes of low grade waste which are sorted, while the environmental impacts are mainly due to the disposal of waste. This is consistent with the results obtained with the other monobjective optimizations. Energy consumption is mainly due to waste collection.

4.1.5. Discussion

The monobjective optimizations have therefore allowed to determine the best management strategy for each objective, and showed the greatest impact areas for each criterion. However, these results should be considered with caution: the model formulation provides an assessment of impacts associated with the copper cycle, with a penalizing assumption, i.e., all costs of collection and sorting, among others, are due to the copper flow management. However, in reality, through selective collection and sorting of

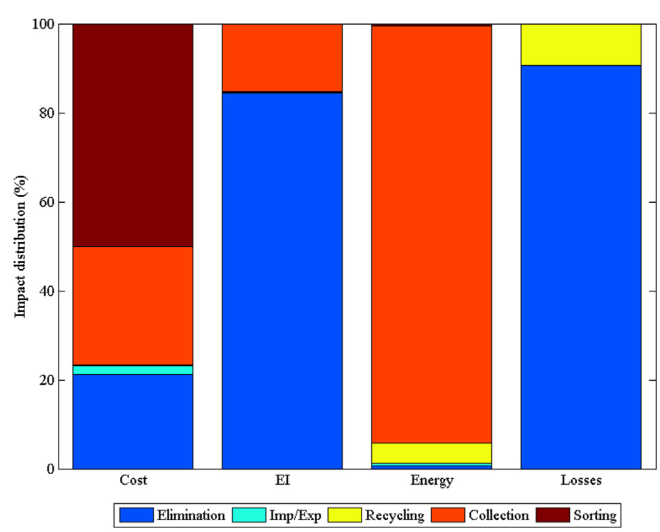

Fig. 10. Distribution of the different impacts when minimizing losses.

waste, metals and many other materials can be recycled, which could lead to an allocation of impacts. The real benefit of the approach is not the absolute values but the comparison of results between the different management strategies.

These results demonstrate the need for the establishment of a multiobjective optimization strategy to study the behavior of the criteria with respect to each other and determine a compromise solution. However, given the size of the problem, with the GA parameters presented above, the computation time for each monobjective optimization is particularly high (about 20:30 for 900 individuals and 1800 generations). Some trials with less individuals or less generations have been run, but in these conditions the results were not reproducible: the best solution was not always found as the model tends to get trapped in local optimums. Considering this, the implementation of a quadriobjective optimization may be viewed as difficult. For this reason, biobjective optimizations have been carried considering the six antagonistic pairs to be separately studied: environmental impacts/costs, environmental impacts/energy, environmental impacts/losses, costs/energy, costs/losses and energy/losses. In this work, only results related to costs and GHG emission minimization will be detailed, as they are both of high priority in view of current issues (United Nation Conference on Climate Change (COP21), 2016).

4.2. Biobjective optimization

4.2.1. Implementation of the biobjective optimization environmental impacts versus costs

A biobjective optimization run has been conducted with the same parameters as the monobjective optimizations. However, due to the mathematical complexity of the problem (e.g. large number of variables, involvement of mixed variables, and especially the equality constraints associated with mass balances that must be rigorously solved), several runs have been implemented to obtain a Pareto front with uniformly distributed solutions. Indeed, as already observed for monobjective optimization with a smaller number of individuals or generations, the model tend to get trapped in local optimums. Some runs with more individuals and more generations have thus been implemented, leading to the following Pareto front (Fig. 11) exhibiting an important set of non-dominated solutions.

4.2.2. Choice of the best compromise solution

To choose a compromise solution from the Pareto front, a multicriteria decision making tool method was used. M-TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, which is a synthetic evaluation method based on the concept of the original TOPSIS (Ren et al., 2007), has been adopted. This method makes a classification of the points of the Pareto front according to their distance with the point *Utopia* ("optimized ideal reference").

The top three points according to M-TOPSIS, shown in Fig. 11, are very close to each other, which is consistent given that the front is continuous. Table 7 presents the criteria values for these three points.

Fig. 12 shows the distribution of the different impacts for the best M-TOPSIS solution. Since the distribution is very similar for points 2 and 3 for the abovementioned reason, these will not be presented in detail.

The decision variables that allow to reach this solution are given in Table 8. They lead to an intermediate solution between individual optimization of costs and environmental impacts (Fig. 13):

- export of low grade wastes (all except WEEE) that will be treated outside the national territory;

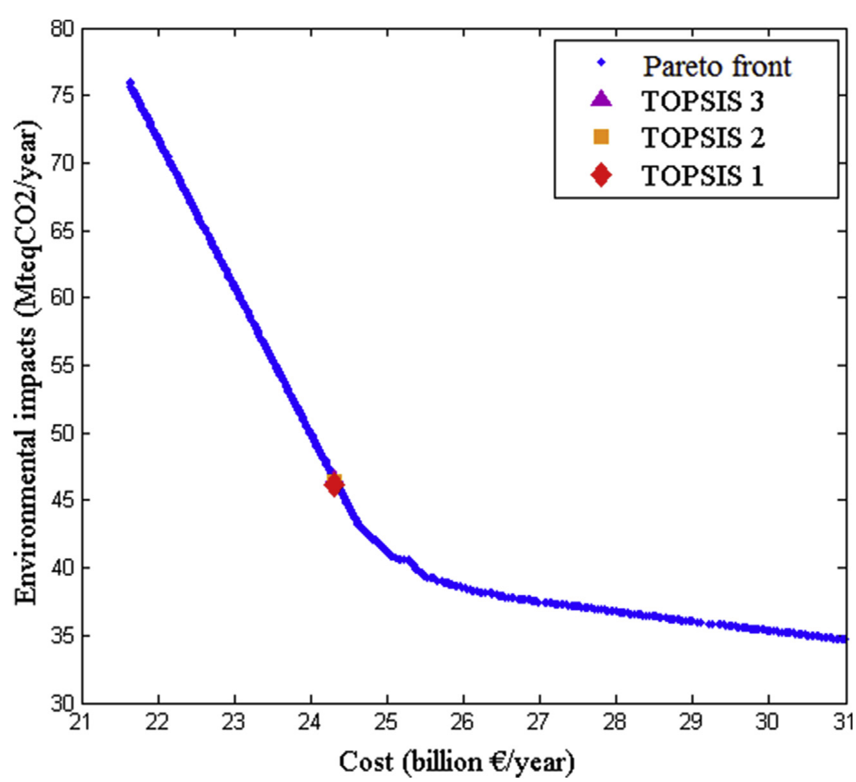

Fig. 11. Cost-Environmental impacts biobjective optimization results: Pareto front.

Table 7
Best ranked M-TOPSIS solutions for the biobjective optimization.

Minimized function	Costs ($G€/an$)	EI ($Mt_{eq_{CO_2}}/an$)	Energy (TWh/an)	Losses (kt/an)	Exp. RC (kt/an)	Exp. alloys (kt/an)
TOPSIS 1	24.3	46.2	157.2	154.6	1422.5	114.7
TOPSIS 2	24.3	46.4	156.7	154.3	1432.9	114.9
TOPSIS 3	24.3	46.5	156.2	154.9	1426.6	114.9

Legend: EI: environmental impacts - Exp.: exports - RC: refined copper.

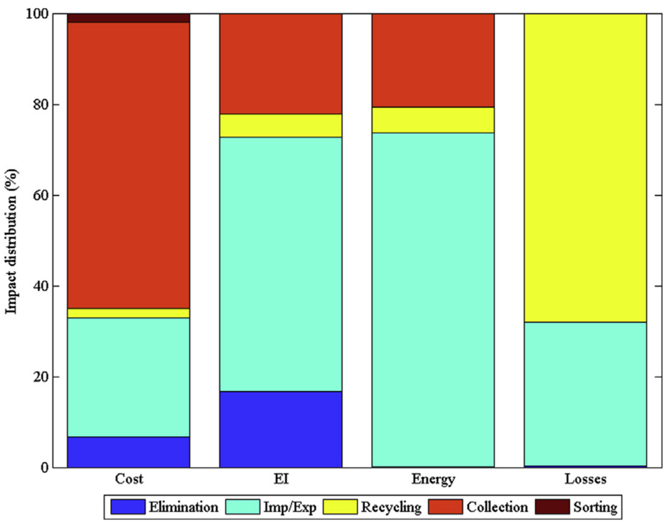

Fig. 12. Distribution of impacts for the best ranked M-TOPSIS of the biobjective optimization.

- import large quantities of WEEE, concentrates, mattes, blisters and scrap (excluding remaining scrap) for recycling and sale of the refined copper produced.

4.3. Towards a quadriobjective optimization

A first attempt towards quadriobjective optimization has been conducted with NSGA II as an optimization strategy for the already mentioned reasons. Yet the complexity of the problem already observed in the biobjective case was confirmed in the quadriobjective case, leading to a failure in the optimization process. To envision this antagonist behavior, a Pareto front combining the six obtained biobjective fronts (environmental impacts/cost, environmental impacts/energy, environmental impacts/losses, costs/energy, costs/losses and energy/losses) has been built. Fig. 14 illustrates the new environmental impacts versus costs Pareto front for this quadriobjective optimization. The biobjective optimization considering environmental impacts and costs that has been previously presented is clearly visible.

A best compromise solution has been obtained according to the previously detailed M-TOPSIS method: Table 9 presents the

Table 8
Decision variables to reach the four identified optimal solutions.

di	Variable	TOPSIS 1	TOPSIS 2	TOPSIS 3
d1	Rate of selectively collected waste	100%	100%	100%
d2	Rate of landfilled I&HW (residual being incinerated)	99%	99%	100%
d2	Rate of landfilled MSW (residual being incinerated)	99%	99%	99%
d2	Rate of landfilled SS (residual being incinerated)	96%	75%	75%
d3	I-E of mixed waste (kt/an)	−2	−4	−4
d7	I-E of WEEE (kt/an)	1530	1534	1534
d8	I-E of ELV (kt/an)	0	0	1
d9	I-E de C&D (kt/an)	−38,134	−37,557	−38,821
d4	I-E of I&HW (kt/an)	−101,024	−100,237	−98,099
d6	I-E of MSW (kt/an)	−30,128	−30,820	−30,818
d5	I-E of SS (kt/an)	−817	−605	−604
d13	Choice between P, S & D for WEEE	2	2	2
d14	Choice between P, S & D for ELV	1	1	1
d15	Choice between P, S & D for C&D	1	1	1
d10	Choice between P, S & D for I&HW	3	3	3
d12	Choice between P, S & D for MSW	3	3	3
d11	Choice between P, S & D for SS	3	3	3
d19	I-E of pure scrap (No.1) (kt/an)	7	17	11
d18	I-E of high grade scrap (No.2) (kt/an)	4	4	4
d17	I-E of low grade scrap (LGS) (kt/an)	1600	1597	1597
d16	I-E of remaining scrap (Residual) (kt/an)	−13	−8	−8
d27	I-E of concentrate (kt/an)	1598	1599	1599
d28	I-E of mattes (kt/an)	548	548	548
d29	I-E of blisters (kt/an)	416	417	417
d23	Choice between P & D for No.1 scrap from WEEE	1	1	1
d22	Choice between P & D for No.2 scrap from WEEE	1	1	1
d21	Choice between P & D for LGS from WEEE	1	1	1
d23	Choice between P & D for alloy scrap from WEEE	1	1	1
d20	Choice between P & D for remaining scrap from WEEE	0	0	0
d26	Flowsheet choice for No.2 scrap	1	1	1
d25	Flowsheet choice for LGS	17	17	17

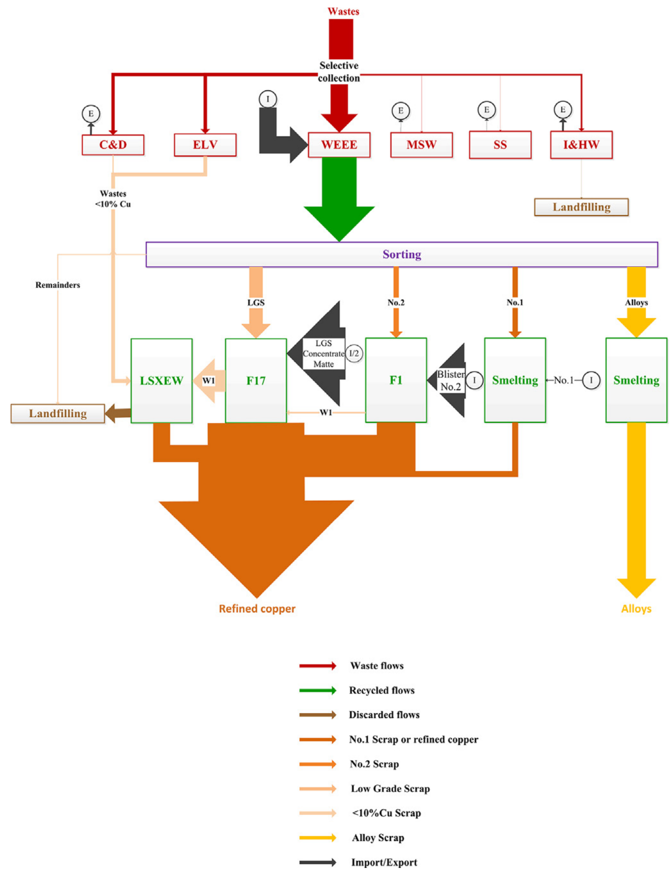

Fig. 13. Representation of flows for the compromise solution obtained with biobjective optimization.

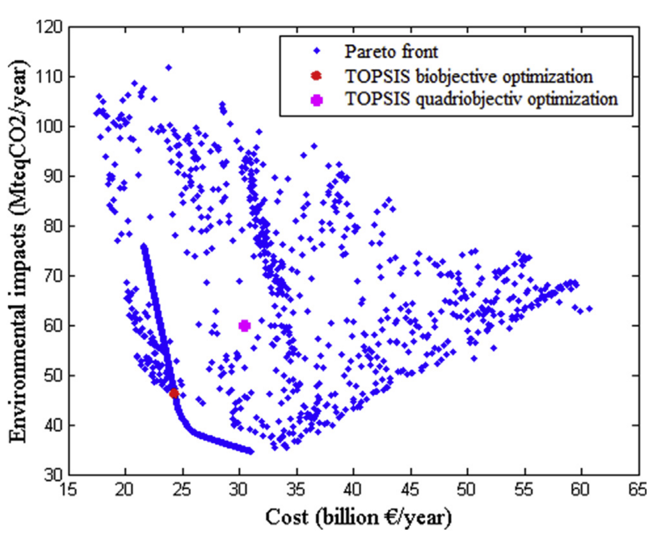

Fig. 14. Pareto fronts of the quadriobjective optimization: EI vs costs with M-TOPSIS results for the bi- and quadriobjective optimizations.

decision variables used to reach this optimal solution compared to the best compromise of the biobjective optimization and Fig. 15 shows the distribution of impact sources for this solution.

It is also possible to compare the best compromise solution obtained by bi- and quadriobjective optimization. Table 10 presents the differences between the objective function final values for both M-TOPSIS best-ranked solution. In addition, by comparing the decision variables and the impact distribution, the resulting strategies are quite different: the rate of landfilled waste is highly decreased with the quadriobjective solution, and importation and exportation strategies are quite different in both solutions. For instance, the quadriobjective solution includes quite large imports of No.1 ad No.2 scrap, which was not the case in the biobjective optimization because of the important cost of these kinds of scraps. These differences in the strategies mainly leads to an increase in the elimination stage and a decrease in the import/export stage in the impact distribution. Regarding objective function values, environmental impacts and costs are slightly more important in the quadriobjective function, while energy consumption is reduced and losses are greatly increased.

4.4. Discussion and perspectives

The use of genetic algorithm has led to propose waste management solutions that optimize costs, GHG emissions, energy consumption and resource losses, as well as a biobjective optimization leading to a compromise solution between cost and environmental impacts. A first quadriobjective optimization result is also proposed, however, given the number of variables and criteria as well as the presence of equality constraint, the GA failed to directly solve this quadriobjective problem.

Some trials on smaller instances of the problem had been successfully solved all along the implementation of this work and no operational alternative was found.

Despite the impossibility to carry out the quadriobjective optimization, biobjective optimizations successfully result in large Pareto fronts that allow to find a compromise for this quadriobjective problem. Regarding these results, different perspectives can be highlighted. The same importance has been given to all four criteria in the decision making process: this can easily be modified and other strategies could be deduced. To overcome the problem complexity and reduce the subsequent computational time, a linearization of the problem formulation is currently being studied to be able to solve it via a mixed integer linear programming solver.

5. Conclusion

A global methodology of resource management optimization at a national scale is proposed, considering all the resource cycle from supplying to waste management. This methodology has been developed and validated on the example of copper management in France involving a multioptimization framework based on a genetic algorithm. Considering all the in- and outflows of the resource, as well as stocks in the technosphere and wastes, the environmental impacts, energy consumption, resource losses and costs have been evaluated and optimized for all possible management strategies.

Mono and biobjective studies have been conducted through a genetic algorithm for copper waste management. This methodological framework has been used to find a compromise solution optimizing simultaneously costs, environmental impacts, energy consumption and losses.

The quadriobjective study could not be performed using directly the genetic algorithm. Indeed, this article has highlighted the difficulty of solving multiobjective problems with many decision variables. The genetic algorithm optimization, which seemed most appropriate given the ability of this method to construct Pareto fronts for multiobjective problems, has finally reached its limits on this complex problem involving strong equality constraints.

The proposed model is a first step in natural resource management and efforts are to be made to make this model really reliable. Some preliminary conclusions can yet be drawn regarding the

Table 9
Decision variables to reach the four identified optimal solutions.

di	Variable	TOPSIS bi	TOPSIS quadri
d1	Rate of selectively collected waste	100%	100%
d2	Rate of landfilled I&HW (residual being incinerated)	99%	33%
d2	Rate of landfilled MSW (residual being incinerated)	99%	16%
d2	Rate of landfilled SS (residual being incinerated)	96%	53%
d3	I-E of mixed waste (kt/an)	−2	−272
d7	I-E of WEEE (kt/an)	1530	751
d8	I-E of ELV (kt/an)	0	125
d9	I-E de C&D (kt/an)	−38,134	−974
d4	I-E of I&HW (kt/an)	−101,024	−72,264
d6	I-E of MSW (kt/an)	−30,128	−20,801
d5	I-E of SS (kt/an)	−817	−18
d13	Choice between P, S & D for WEEE	2	2
d14	Choice between P, S & D for ELV	1	3
d15	Choice between P, S & D for C&D	1	3
d10	Choice between P, S & D for I&HW	3	3
d12	Choice between P, S & D for MSW	3	3
d11	Choice between P, S & D for SS	3	3
d19	I-E of pure scrap (No.1) (kt/an)	7	316
d18	I-E of high grade scrap (No.2) (kt/an)	4	145
d17	I-E of low grade scrap (LGS) (kt/an)	1600	506
d16	I-E of remaining scrap (Residual) (kt/an)	−13	−479
d27	I-E of concentrate (kt/an)	1598	1321
d28	I-E of mattes (kt/an)	548	476
d29	I-E of blisters (kt/an)	416	355
d23	Choice between P & D for No.1 scrap from WEEE	1	1
d22	Choice between P & D for No.2 scrap from WEEE	1	0
d21	Choice between P & D for LGS from WEEE	1	0
d23	Choice between P & D for alloy scrap from WEEE	1	1
d20	Choice between P & D for remaining scrap from WEEE	0	0
d26	Flowsheet choice for No.2 scrap	1	1
d25	Flowsheet choice for LGS	17	12

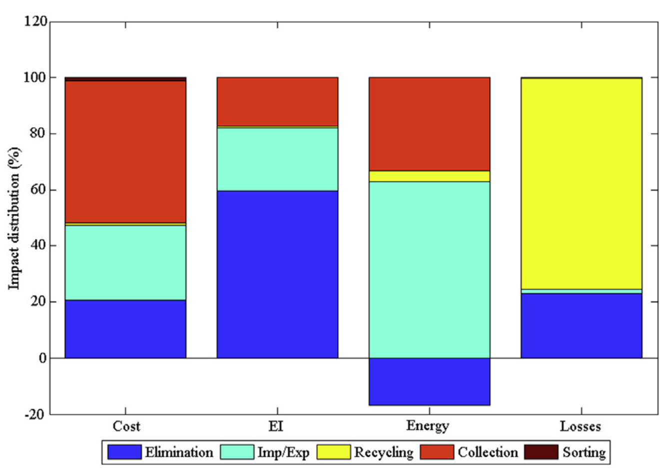

Fig. 15. Distribution of impacts for the best ranked M-TOPSIS of the quadriobjective optimization.

establishment of a sustainable resource management. Under current conditions, it appears that the recycling of most highly concentrated copper waste is the only interesting strategy that optimizes all the criteria. The compromise solutions obtained favours the development of the recycling of waste from electrical and electronic equipment. However, if the cost of resources (raw materials) increases or if new recycling processes of waste with low copper content are to be developed, changes may be expected. It should also be emphasized that, according to the different simulations that have been performed, even if all the wastes are recycled, the current amount of copper contained in the waste does not meet demand, and that imports are necessary in all scenarios. This model should thus be extended at the world scale to define if it is possible to reach a sustainable cycle only through a good management strategy, or if in the future copper will have to be replace with other materials for given use to avoid scarcity.

Once the aforementioned perspective implemented, longer term perspectives to this work will be to vary the system input data, especially economic data, to identify the value of primary copper cost that makes the recycling of all waste flows interesting. The model developed here can therefore be adapted very easily, by adding or removing constraints and criteria to evaluate management scenarios based on economic, regulation and environmental constraints. Another study could focus on opportunities to reduce the copper demand and the effects it would have, for example by replacing it by other materials in some applications.

Finally, in this study all impacts have been allocated to copper while recycling of scrap will lead to the recovery of other metals. An even more systemic approach should be performed to implement and interconnect different metal cycles.

Table 10
Comparison of best ranked M-TOPSIS solutions for the bi- and quadriobjective optimizations.

Minimized function	Costs (G/an)	EI ($Mt_{eq_{co_2}}/an$)	Energy (TWh/an)	Losses (kt/an)	Exp. RC (kt/an)	Exp. alloys (kt/an)
TOPSIS bi	24.3	46.2	157.2	154.6	1422.5	114.7
TOPSIS quadri	30.5	59.8	82.1	1086.4	424.9	59.3

Legend: EI: environmental impacts - Exp.: exports - RC: refined copper.

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Appendix A. Data used for impact calculation

Appendix A.1. Data used for economic impact calculation

Following data and hypothesis have been used for calculation of the copper cycle cost.

Table A.1
Data used for costs calculation

Impact	Value	Source
Costs related exclusively to recycling processes, calculated from energy consumption		
Electricity	0.06542 €/kWh	Rates <240 kVA EDF (+43.44/subscription)
Electricity	0.04474 €/kWh	Rates > 240 kVA EDF (+69.96/subscription)
Oil	0.1 €/kWh	Rate
Costs associated with waste collection (selective or not)		
MSW selective collect	151 €/t	(Andrup et al., 2011)
Other wastes selective collect	66 €/t	(Andrup et al., 2011)
Non-selective collect	151 €/t	Assumed equal to MSW selective collect cost
Costs associated with waste disposal (landfill or incineration) (Andrup et al., 2011)		
Landfilling	64 €/t	price of waste landfilling
Incineration	9–33 €/t	price of incineration of waste, to which must be removed the sale of electricity (fixed rate: 0.06 €/kWh for an energy production of 550kWh/t)
Costs associated with waste sorting to extract scrap		
Sorting	151 €/t of sorted waste	assumed to be equal to the costs of selective collection of MSW
Costs attributed to imports and exports (copper, waste, etc.).		
Sorted wastes	80 €/t	0.0272 $L/tkm \times 2,000km$ with costs of approximately 1.5/L
Mixed wastes	165 €/t	Hypothesis: in addition to transport costs, you have to pay the country to accept them
Scrap selling cost		
No.1	5900 €/t	pure scrap prices on the market
No.2	5550 €/t	price of high quality scrap on the market
LGS	1000 €/t	price of low grade scrap on the market (hypothesis: 5000 /t_{Cu} with an average of 20% copper)
Alloys	4200 €/t	price of alloy scrap on the market
Remainder	0 €/t	price of remainder scrap on the market (hypothesis: this has no market value since copper is too dilute)
Refined copper	6000 €/t	refined copper price on the market
Concentrate	40 €/t	market price
Matte	1000 €/t	market price
Blister	3000 €/t	market price

Appendix A.2. Data used for environmental impacts calculation

The following data and assumptions were used to calculate the total environmental impact expressed in equivalent CO_2 mainly taken from the database EcoInvent (Classen et al., 2009). It should be noted that the impacts of recycling processes have been calculated from the energy and material consumption of the processes.

Table A.2
Data used for environmental impacts calculation

Impact	Value	Source
Recycling-related impacts		
Electricity	0.0262 kg_{eqCO_2}/kWh	EcoInvent "Electricity, medium voltage, at grid/FR"
Oil	0.358 kg_{eqCO_2}/kWh	EcoInvent: Average of "Fuels Oil": 0.500kg_{eqCO_2}/kg, with a calorific value of about 12kWh/kg
Water	0.0015 kg_{eqCO_2}/kWh	Average of industrial waters (0.001kg_{eqCO_2}/kg) + energy to heat the water at 1200 °C
Oxygen	0.5307 kg_{eqCO_2}/kWh	EcoInvent "Oxygen, liquid, at plant/RER" 0.408 kg_{eqCO_2}/kg and electricity consumption 0.76,883 kWh/kg
Silica	0 kg_{eqCO_2}/kWh	Raw material
Impacts associated with waste collection (selective or not)		
MSW selective collect	92 kg_{eqCO_2}/t	EcoInvent "Transport, municipal waste collection, lorry 21t/CH" (hypothesis: 70km)
Other wastes selective collect	46 kg_{eqCO_2}/t	Half as much as brought by individuals or industries
Non-selective collect	92 kg_{eqCO_2}/t	Assumed equal to MSW selective collect impacts
Impacts associated with waste disposal (landfill or incineration)		
Landfilling	300 kg_{eqCO_2}/t	EcoInvent: 7.09 kg_{eqCO_2}/t for inert waste landfill but > 300 kg_{eqCO_2}/t for the landfilling of residual waste
Incineration	505 – 14.41 kg_{eqCO_2}/t	EcoInvent "Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH": 505 kg_{eqCO_2}/t waste, but it must be considered that energy is recovered: 550 kWh_{elec}/t are recovered, and according to EcoInvent, the electricity produced in France has an impact of 0.0262 kg_{eqCO_2}/kWh
Impacts associated with waste sorting to extract scrap		
Sorting	6.10^3 kg_{eqCO_2}/t	Manual sorting, negligible impacts
Impacts attributed to imports and exports (copper, waste, etc.).		
Waste transport (all types)	125 kg_{eqCO_2}/t	EcoInvent "Transport combination truck gasoline powered" (hypothesis: 2000km)
Impact attributed to imported products (besides transport)		
Concentrate	450 kg_{eqCO_2}/t	EcoInvent "copper concentrate, at beneficiation"
Matte	525 kg_{eqCO_2}/t	Impact between that of the concentrate and the blister
Blister	568 kg_{eqCO_2}/t	EcoInvent "copper, blister-copper, at primary smelter/kg/RER"
Refined copper	2875 kg_{eqCO_2}/t	EcoInvent "copper, primary, at refinery" (average)

Appendix A.3. Data used for energy consumption calculation

Following data and hypothesis have been used for calculation of energy consumption linked to copper cycle.

Table A.3
Data used for energy consumption calculation

Impact	Value	Source
Energy (and material) consumption of the processes		
Calculated from the data presented in the tables by process		
Energy consumption related to waste collection (selective or not)		
MSW selective collect	290 kWh/t	EcoInvent: 0.336 kg_{diesel}/tkm with heating power 44.8MJ/L, or

(*continued on next page*)

Table A.3 (*continued*)

Impact	Value	Source
		$12.44 kWh/kg$, so $4.1813 kWh/tkm$, retained average distance: 70 km
Other wastes selective collect	145 kWh/t	half as much because they are bring by the people
Non-selective collect: energy consumption of the collect	290 kWh/t	Assumed equal to MSW selective collect energy consumption
Energy consumption associated with waste disposal (landfill or incineration)		
Landfilling	1.25 kWh/t	Very low energy consumption, only to feed trucks: 10 km to raise
Incineration	−550 kWh/t	Power generation by incineration: PCI of waste is such that 2.2 $MWh_{thermal}/t$ are recovered, if electric energy is considered, this is multiplied by a yield of 25%
Energy consumption associated with waste sorting to extract scrap		
Sorting	1 kWh/t	Manual sorting, negligible energy
Energy consumption attributed to imports and exports (copper, waste, etc.).		
All wastes	600 kWh/t	EcoInvent: 0.0272 L_{oil}/tkm or 54.4 L/t for 2000km, with a calorific value of 38,080 kJ/L or 10.58kWh/L, so 575 kWh/t
Energy consumption attributed to imported products (besides transport)		
Refined copper	8300 kWh/t	Average of different studies: Jdid and Blazy (2002): production from ore = 105 to 110MJ/kg_{Cu}, or 29,166.67 to 30,555.56kWh/t_{Cu}, but in many other studies, it is rather between 25 and 30 MJ/kg_{Cu} (for example Fthenakis et al. (2009)), about 8300 kWh/t_{Cu}
Concentrate	166 kWh/t	EcoInvent “copper concentrate, at beneficiation”
Matte	2324 kWh/t	Energy between that of the concentrate and the blister
Blister	6354 kWh/t	EcoInvent “copper, blister-copper, at primary smelter/kg/RER”

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